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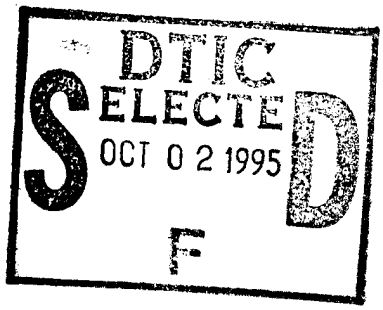

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High-heat environments impair work performance and can compromise combat mission success. Lack of heat dissipation poses a serious problem to personnel who perform work in noxious environments. To decrease the incidence of heat injury and increase performance capability, microcooling technologies have been developed for personnel working in encapsulated garments. Currently, the effectiveness of microclimate cooling systems (MCS) for females has not been determined. Due to gender differences in thermoregulation and anthropometry, some MCS may confer a greater advantage in women. In the proposed studies, cooling will be provided with a whole-body water-cooled system, a vest air-cooled system, and a vest phase-change material system. The proposed study will determine the effectiveness of microclimate cooling as a countermeasure to heat stress for females.

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INTRODUCTION

1. Problem

The Presidential Commission on the Assignment of Women in the Armed Forces has recommended the military adopt a gender-neutral assignment policy.[1] In 1993, Admiral Frank Kelso, the Chief of Naval Operations (CNO), who was then acting Secretary of the Navy, recommended expanding the number of jobs open to women. He also stated the long-term objective was to make all naval positions available to women.[2] The current CNO has likewise issued a mission statement allowing female personnel to fill a wider range of billets.[3] To ensure occupational safety and military readiness, the Presidential Commission suggested that fitness requirements be developed for job classifications which necessitate immoderate physical strength or cardiovascular capacity.[1] Although fitness requirements have not been adopted, women in the military are performing physically demanding jobs. In their roles, women are not only engaged in heavy work, but in some cases their efforts are exacerbated by heat stress. Uncompensated heat stress can lead to a loss in performance capability and efficiency. In an attempt to reduce the incidence of heat-related injuries in the Navy, microclimate cooling systems (MCS) have been developed as a countermeasure to heat stress.

MCS have been implemented in many military tasks which require work in noxious environments. MCS are currently employed by personnel who work in hot environments and/or in protective encapsulating garments (e.g., chemical, biological, radiological ensembles and firefighting ensembles). Over the last 5 years, the Naval Health Research Center (NHRC) has investigated the effectiveness of MCS. The demands of the MCS user to transfer heat energy, the physical load imposed by a MCS, and the need for logistical support have been determined. These issues have not been addressed in relation to the female population.

2. Background

Current models of thermoregulation suggest that established gender differences in four areas may influence the effectiveness of a MCS in females when compared to males. These gender differences are in physical fitness, anthropometry, and sweat rate.

The first difference, physical fitness, has been shown to differ between male and female military personnel. Physical strength in female recruits after basic training was 60% of the upper-body and 67% of the lower-body strength of the male recruits.4. Military females have 75% of the aerobic ability[5] and 30% longer 1.5 mile run times[6] than military males. Considering that some of the MCS

weigh up to 16 pounds, use of this equipment requires women to lift a greater percent of maximal capacity when compared to men. Additionally, the metabolic cost associated with wearing the MCS requires females to perform work at a higher percent of their aerobic ability. Thus when using a MCS, onset of muscular fatigue may be hastened in females and could produce a greater impairment in performance of submaximal exercise in females than males. Thus, the weight of a MCS may be problematic and could offset the cooling advantage in females.

The second difference, anthropometry, has long been noted. Anthropometric studies involving 214 women and 602 men found that Navy women were on the average 5 inches shorter and 50 pounds lighter than the men.[7,8] The smaller body size of women compared to men may create a logistical problem for fitting of a MCS. In addition, due to the presence of sensitive breast tissue, placement of a cooling apparatus on the thorax may be intolerable. This is especially evident for the ice vest currently used aboard ship. Another gender difference in anthropometry, distribution of muscle mass, may influence decisions in regard to placement of MCS on the body. In a military population, women have 30% less muscle mass (54 pounds) than men[9]; with relatively more mass distributed in the legs than the arms.[10] Because heat extraction is enhanced in areas overlying active muscle tissue,[11] location of muscle mass impacts on decisions for regional placement of MCS.

Guidance for the type of MCS to be used (e.g., air, water, or phase change) can also be dependent on anthropometry. Because women have a greater surface-to-mass ratio[6,7,8] and a greater mean skin temperature[12] a water-cooled MCS may be the most effective type of system for females.

The third difference, sweat rate, has been found to be greater in men than in women.[13,14,15] Sweat rate is an important thermoregulatory response to physical performance in the heat and can be a determining factor in mission success, heat illness, fluid consumption requirements, and type of MCS employed. A greater sweat rate confers a larger capacity for heat loss via evaporation. Since air-cooling MCS function by increasing evaporative heat loss, sweat rate in females may be insufficient to employ air-cooled MCS.

3. Purpose

Effective microclimate cooling is essential for prevention of heat strain in hot (and noxious) environments, and currently the effectiveness of MCS for females has not been determined. This study was initiated in response to a Congressional request for research on women's health issues related to service in the armed forces. The purpose of this study is to examine the occupational hazard of performing work in a high-heat environment, while

encapsulated in a protective ensemble, and to explore possible countermeasures. This study will investigate MCS as a countermeasure for heat stress in females.

4. Approach

Various MCS currently employed in the armed services will be evaluated for efficacy and operational feasibility for females. Comparisons will be made between cooling provided by a whole-body water-cooled system, a vest air-cooled system, and a phase-change material vest. Information from this project will be used to optimize the design of operationally feasible MCS that maintain and/or enhance performance of female personnel in high-heat environments.

EXPERIMENTAL METHODS

Subjects: A total of 16 male and 16 female military personnel will serve as subjects. The volunteers will be recruited from military units from San Diego.

Design: Each volunteer will participate in one preliminary visit and four 120-min experimental trials at 44°C (110°F) and 30% relative humidity (RH). In the experimental trials, the volunteer will perform exercise by walking on an elevated treadmill while wearing a chemical, biological, radiological ensemble (without a mask). The participant will complete the following four experimental conditions:

1) No Cooling - No MCS will be worn under the CBR ensemble.

2) Water Cooling - Under the CBR ensemble a water-cooled suit calorimeter will be used to remove excess heat (i.e., environmental and metabolic heat) from the volunteer. The suit consists of a nylon garment embedded with a network of flexible plastic tubing which have a small diameter. The tubes will be in direct contact with approximately 20% of the body surface area. A total of 157 meters of tubes will be distributed over six separate body regions: head/neck (11%), arms (18%), upper torso (15%), lower torso (14%), thighs (18%), and lower legs (24%). Water will be circulating to the tube suit from a temperature-controlled reservoir. Both the inlet water temperature (T_i) and the water velocity will be manipulated. In this study, water velocity will be kept low and constant (300 to 500 g/min), and T_i will be kept in the range of 15°C to 30°C. Inlet and outlet water temperatures in each region will be measured with precision thermistors. Water flow will be measured with a turbine flowmeter. Both water flow and temperature measurements will be averaged and recorded over 2-min intervals. The rate of heat removal from each body region will be calculated from the mass flow of water through the tubes and the change in

water temperature across the region. Additionally, sewn into the suit are six skin thermistors which will be recorded and displayed at 2-min intervals.

3) Air Cooling - An air-cooling MCS will be worn under the CBR ensemble. The torso air-cooling system consists of a nylon vest which has an interior distribution system in the front and back through which air passes. The air will be delivered to the vest by a temperature-controlled system designed by Carlson, Inc.

4) Phase Change Cooling - Under the CBR ensemble, the volunteer will wear a torso cooling vest manufactured by Steele. The vest consists of heavy canvas in which pockets are sewn. Packets of phase change material (corn starch and water) which have been frozen to -20°F will be inserted into the vest pockets. The vest and packets together weigh approximately 12 pounds.

Preliminary Visit Procedure and Measurements:

Procedure:

During the preliminary visit, the volunteer will sign the informed consent which outlines the general purpose and procedures of the study and undergo initial screening by the medical monitor. Initial screening will consist of a review of the volunteer's medical record and/or medical history questionnaire and a 12-lead electrocardiogram (taken at rest). The female volunteer will provide a urine sample which will be tested for the presence of human chorionic gonadotropin (hCG). Upon approval for participation, the volunteer will have anthropometric sites, pilocarpine-stimulated SR, and maximal oxygen consumption ($\dot{V}O_2max$) measured.

Measurements:

hCG Urine Test - Urine samples will be obtained from female volunteers. The presence/absence of hCG will be detected with an immunoenzymatic assay.

Anthropometric Measurements - Body composition of each subject will be assessed using skinfold and body circumference measurements. Percent body fat and lean body mass will be calculated using regression equations presented in the literature.

Pilocarpine Stimulated Sweat Rate - Maximal SR in a small region on the forearm will be measured using the Macroduct system. Gel disks impregnated with pilocarpine will be placed on the forearm. A small iontophoretic current (1.5 mA) will be applied to the disks, which will transport pilocarpinium ions to the sweat glands to stimulate optimal sweating. The sweat will be collected and the

volume measured.

$\dot{V}O_2$max (treadmill) Measurement - This test will be conducted on a motorized treadmill using an incremental load protocol. Each subject will exercise to volitional exhaustion, or the test will end when the criteria for $\dot{V}O_2$max is achieved, i.e., no increase in HR or $\dot{V}O_2$ with an increase in work load, and a respiratory exchange ratio of greater than 1.00.

Experimental Trial Procedure & Measurements:

Procedure:

Prior to each experimental trial, the volunteer will be instructed to avoid heat exposure, alcohol consumption, and exercise on the day before experimentation. The volunteer will be instructed to drink at least 24 ounces of fluid on the night prior to the trials.

On the day of each heat exposure trial, the volunteer will report to the environmental chamber at the same time of day. Upon reporting to the laboratory, specific gravity of the urine will be assessed to ensure proper hydration. A specific gravity of ≤ 1.028 will be required to begin testing. Female volunteers will provide a urine sample to be tested for the presence of hCG. A nude weight will be recorded by the volunteer to be used to calculate total-body SR. Then, total-body water will be assessed via bioimpedance. After 20 min of seated rest, 10 ml (0.3 oz.) of blood will be drawn from a superficial vein in the forearm to estimate plasma volume and determine plasma protein concentration.

After these preliminary measurements, the volunteer will be instrumented with eight skin thermistors, a rectal thermistor, six heat flux sensors, and a HR monitor. The volunteer will insert the rectal thermistor. With assistance, the subject will put on the MCS, a pair of coveralls, and a CBR ensemble in a modified MOPP III configuration (with boots and gloves added but no mask). Once instrumented, the volunteer will be reweighed.

Then the volunteer will remain seated for approximately 20 min. During this time, skin blood flow will be measured using a laser doppler and forearm blood flow will be determined using a plethysmography.

Once these measurements are taken, the volunteer will be escorted into the environmental chamber set at 44°C and 30% RH. The volunteer will be supervised by a corpsman while in the chamber. Upon entering the chamber, the volunteer will begin a protocol of 10 min rest/50 min moderate exercise ($\dot{V}O_2 \approx 1.2$ L/min) for 120 min, or until one of the criteria for termination of the experiment is

reached. The exercise will consist of walking on an elevated treadmill. Oxygen consumption and cardiac output will be measured twice during each exercise session. Forearm blood flow and skin blood flow will be determined during the rest period. Body temperature will be recorded throughout the experiment with a data logger. HR will be measured and recorded via a chest strap sensor/transmitter and wristwatch receiver. HR and T_{re} will be monitored every 5 min. Skin temperature in eight regions will be recorded and displayed at 2-min intervals. Thermal sensation and perceived exertion will be recorded every 10 min. The volunteer will be permitted to consume water at will.

The volunteer will alternate 10 min of rest with 50 min of exercise, for 120 min or until a criteria for termination of the experiment is reached. Criteria for termination of heat exposure include:

1) Rectal temperature of 39.5°C during exercise;
2) Rectal temperature of 39.2°C during rest;
3) 90% of maximal heart rate during exercise for 5 min;
4) 80% of maximal heart rate during rest for 5 min; value obtained;
5) Rectal temperature increases greater than 0.6°C in 5 min, excluding the initial 10 min of exercise;
6) The subject has chills, sweat cessation, nausea, vomiting, retching, syncope, cramps, dizziness or disorientation;
7) If the subject wishes to withdraw from the study;
8) 120 min maximum time limit is reached;

Upon termination, the volunteer will exit the chamber and be weighed while fully equipped. Twenty minutes after termination of the test, the volunteer will have 10 ml (0.3 oz.) of blood drawn from a superficial vein in the forearm and total-body water measured via bioimpedence.

Measurements:

Total-Body Water Measurement - A bioimpedence analyzer will be used to determine total-body water.

Forearm Blood Flow - Blood flow will be determined by plethysmography.

Skin Blood Flow - To measure capillary blood perfusion, a doppler technique which involves placing an electrode on the surface of the forearm and sending a high frequency light beam through the electrode. The output will be qualitative data and will be proportional to blood flow, volume, and velocity.

Total-Body and Local Sweat Rate Measurement - Nude body weight of each subject will be measured prior to and after the heat exposure. Total-body sweat loss will be calculated as the body weight loss, corrected for urine output, and fluids consumed.

Skin Temperature Measurement - Eight skin thermistors will be placed on the face, chest, back, arm, hand, thigh, lower leg, and foot for the determination of local skin temperature and calculation of mean skin temperature. The skin thermistors will be connected to a digital logger for continuous visual monitoring and recording data.

Heat Flux Measurement - Six heat flux sensors will be placed on the skin surface at the head, chest, back, arm, thigh, and lower leg to define heat flow (Radiative + Convective).

Rectal Temperature Measurement - To measure T_{re}, each subject will insert her/his own disposable rectal thermistor to a depth of 15 cm (6 inches) beyond the anal sphincter. The rectal thermistor will be connected to a Squirrel digital logger for continuous visual monitoring and recording data.

Heart Rate Measurement - HR will be recorded by a monitor that consists of electrodes on a chest strap which continuously transmits a signal to a wristwatch receiver.

Oxygen Uptake Measurement - Oxygen uptake will be measured during exercise by open-circuit spirometry using either a manual or an automated expired gas collection system.

Cardiac Output Measurement - Cardiac output will be determined using the noninvasive carbon dioxide (CO_2) rebreathing technique[9]. This method estimates mixed venous CO_2 pressure (P_vCO_2) using a closed lung-bag system as an aerotonometer. Arterial PCO_2 (P_aCO_2), is determined from end-tidal CO_2 ($P_{et}CO_2$) values. P_vCO_2 and P_aCO_2 are converted to arterial and venous CO_2 dissociation equation. Cardiac output ($\dot{Q}$) is calculated using the Fick equation:

$$\dot{Q} = VCO_2 / (P_vCO_2 - P_aCO_2)$$

Where VCO_2 equals the volume of expired CO_2 as determined by open-circuit spirometry. The rebreathing bag will contain a known concentration of CO_2 (9% to 12%) and the remainder O_2 (88% to 91%). The subjects will take several breaths from the bag in order to reach a PCO_2 equilibrium between the bag, lungs, and pulmonary artery.

Plasma Volume Change - A change in plasma volume will be determined by comparing pre and post values of hematocrit (HCT) using the following formula:

A = 100 ÷ 100 - pre HCT B = (pre HCT - post Hct)÷ post HCT

Plasma Volume Change = (A x B) x 100%

Psychophysiological Questionnaires: The subjects will be asked to rate, on a numerical scale, the following psychophysiological variables. Ratings will be taken every 10 min.

(1) Ratings of Perceived Exertion (RPE) - how hard the subject is working at that specific time point.
(2) Thermal Sensation (TS) - how hot the subject feels at that specific time point.

RESULTS

Funding was received 25 January 1995.

Supplies have been procured. Contracts for labor support have been let, and contractors are on board. Technical training associated with this study has been completed. Needed modifications to the thermal chamber controllers have been completed. Modifications to the individual air-cooling systems, to allow air flow rates and temperature to be measured, have been completed. Contracts for the tube suits for application of liquid cooling were let, and prototype suits were received. These had to be sent back for modifications as the tubes did not uniformly contact the skin. Suit modifications are now almost completed, and it is anticipated that modified suits will be received within the week. The study should begin prior to the end of FY95.

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